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SOME METROLOGICAL PROPERTIES OF AN ELASTOMAGNETIC SENSOR OF PRESSURE FORCE

A. Hodulíková, D. Kováč
Technical University of Košice
Park Komenského, 3, Košice, 04001, Slovak Republic.
E-mail: anna.hodulikova@tuke.sk, dobroslav.kovac@tuke.sk

In its first part the presented article deals with metrological properties of elastomagnetic pressure force sensor with nominal value 120kN. which was designed and produced on Department of Theoretical Electrical Engineering and Electrical Measurement FEI TUKE. Elastomagnetic pressure force sensor is based upon utilization of Vilari´s effect and belongs to group of nonlinear systems. Second part of the article deals with verification of output voltage elastomagnetic pressure force sensor in order to verify if the magnetic induction values obtained by 3D model computer simulation in COSMOS/EMS environment are the same as experimental results obtained by measurements of output voltage.

Key words: elastomagnetic sensor, metrological properties, simulation, output voltage.

ДЕЯКІ МЕТРОЛОГІЧНІ ВЛАСТИВОСТІ ЕЛАСТОМАГНІТНИХ ДАТЧИКІВ СИЛИ НАТИСКАННЯ

А. Ходулікова, Д. Ковач
Технічний університет Кошице
Парк Коменского, 3, м. Кошице, 04001, Словаччина.
E-mail: anna.hodulikova@tuke.sk, dobroslav.kovac@tuke.sk

У першій частині даної роботи йдеться про метрологічні властивості еластомагнітних датчиків сили натискання з нормальним значенням 120 кН, які було спроектовано та виготовлено на кафедрі електричної інженерії та електричних вимірювань FEI TUKE. Еластомагнітні датчики сили натискання засновано на використанні ефекту Віларі та належать до групи нелінійних систем. Другу частину роботи присвячено перевірці вихідної напруги еластомагнітних датчиків сили натискання з метою визначення відповідності значень магнітної індукції, отриманих за допомогою комп'ютерної симуляції тривимірної моделі в середовищі COSMOS/EMS, експериментальним результатам, отриманим шляхом вимірювання вихідної напруги.

Ключові слова: електромагнітні датчики, метрологічні властивості, симуляція, вихідна напруга.

PROBLEM STATEMENT. Elastomagnetic sensor´s belong to group of magnetostrictive sensors, where magnetic and mechanic states of ferromagnetic materials affect each other. In case of elastomagnetic sensors, when affected by mechanical pressure, magnetic properties of ferromagnetic object are subject to change. It is manifested by change of magnetic permeability.The advantage of elastomagnetic pressure force sensor (EMS) is their sensitivity and possibility of usage of output value without the need of signal amplification.
The disadvantage of these sensors is the fact, that they function like transformer. For calculation of output voltage, the value of magnetic induction is needed and it can be obtained only by solving the magnetic field in EMS core. Because of this, there is room for many rogue effects, which are characteristic for magnetic circuits like heat losses, magnetostriction, hysteresis.

EXPERIMENTAL PART AND RESULTS OBTAINED. *ELASTOMAGNETIC SENSOR EMS–120 kN.* The pressure force sensor EMS-120kN is an input block of a measuring system., Fig. 1. One of criteria of sensor applicability are its errors.The standarrd IEC 60 770 [3] defines inaccuracy δ_{acc}, measured error δ_{me}, repeatability δ_{rep}, hysteresis δ_{hys}, linearity error δ_{lin} and process of measurement evaluation. Sensor error presented in Fig. 1 are computed in compliance with the standard. The error of transfer characteristic as a difference between measured quantity and corresponding ideal output value. Generally, percentage error is expressed in the percentage span of ideal output and it is defined as follows:

$$e = \left(\frac{y_{measured} - y_{ideal}}{y_{\max} - y_{\min}} \right) .100\,\%. \qquad (1)$$

Non-linearity δ_{lin} is defined like the maximum of difference between the average characteristic y_{mean} (from measured characteristics) and specific characteristic y_{ideal} (the straight line):

$$\delta_{lin} = \left(\frac{y_{mean} - y_{lin}}{y_{\max} - y_{\min}} \right)_{\max} .100\,\%, \qquad (2)$$

where the straight line $y_{lin} = K_0 + K_1.x$ is calculated by the least square method. This case is called independent non-linearity. The error of hysteresis δ_{hys} causes that sensor gives different output values $y_{\uparrow}$ a $y_{\downarrow}$ for the same input values x depending on the increase and decrease of input quantity, respectively, and it is defined as follows:

$$\delta_{hys} = \left(\frac{y_{\uparrow} - y_{\downarrow}}{y_{\max} - y_{\min}} \right)_{\max} .100\,\%. \qquad (3)$$

δ_{acc} = -3,16 % , 5,24 %,; δ_{me} =4,63 % ;
δ_{rep} = 1,65 %;
δ_{hys} = 2,13 %;
δ_{lin} = 1,9 %.

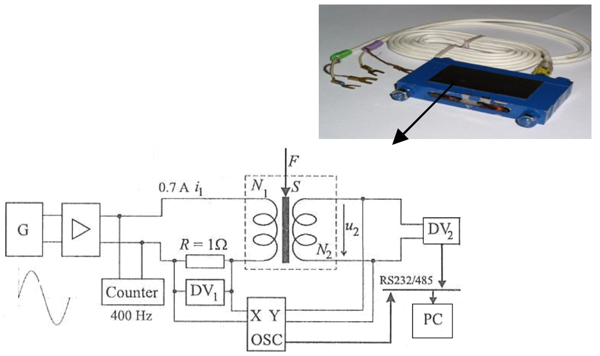

Figure 1 – Measuring apparatus connection with EMS-120kN; generator (G), pressure sensor (S), digital voltmeters (DV1 and DV2), oscilloscope (OSC), computer (PC), acting force (F)

The output sensor characteristic is depicted in Fig. 2. It consists of $U_{2\uparrow}$ (if force F increases from 0 kN to 120 kN) and $U_{2\downarrow}$ (if force F decreases from 0 kN to 120 kN). On order to enable converrsion of the output sensor voltage into the meawsured force, a straight line ($U_{2lin} = -5,8464F + 1639,2$) is calculed by the least square method.

Then the transfer characteristic is obtained:

$$F = -\frac{U_2 - 1639,2}{5,8464} \text{ [kN, mV]} \tag{4}$$

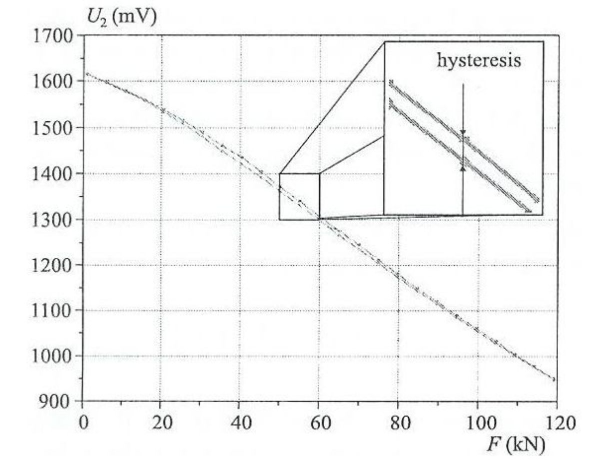

Figure 2 – Output sensor characteristic

OUTPUT SIGNAL OF ELASTOMAGNETIC SENSOR OF PRESSURE FORCE. From metrological point of view it is suitable, that output signal should be related to input signal. Because of zero force, the output signal will be nonzero, it will be better to determine only the difference in voltage $\Delta u_2(t)$ between voltage when the sensor is loader $u^F_{2(p\neq 0)}(t)$ and when the sensor is idle $u_{2(p=0)}(t)$. If the magnetostriction coefficient of chosen ferromagnetic material will be positive, output voltage with increasing pressure will begin to fall and $\Delta u_2(t)$ (useful signal) will become negative, therefore we need to adjust the equation:

$$\Delta u_2(t) = \left| u_2^F(t) - u_2(t) \right| = \\ = \left| -N_2 \left\{ \frac{\partial}{\partial t}\left[\int_S \mathbf{B}^F(t).d\mathbf{S} \right] - \frac{\partial}{\partial t}\left[\int_S \mathbf{B}(t).d\mathbf{S} \right] \right\} \right|, \tag{5}$$

In order to express the effective value of sensor´s output voltage it is convenient to assume that the progress of sensor´s magnetic induction and induced voltage $\Delta u_2(t)$, (Fig. 5,Fig. 6) is harmonic like the feeding current of primary winding. $i_1(t) = I_{m1}\sin\omega t$ [A], when I_{m1} is the maximum value of current $i_1(t)$ and $\omega = 2\pi f$ is the angle frequency of time changes of awaking current and for effective value of voltage U_{2ef} a ΔU_{2ef} is:

$$U_{2ef} = \sqrt{\frac{1}{T}\int_0^T u_2^2 dt} = \sqrt{\frac{1}{T}\int_0^T \left[-N_2 \left(\int_S \boldsymbol{B}(\boldsymbol{r},t) d\boldsymbol{S} \right) \right]^2 dt}\,; \tag{6}$$

$$\Delta U_{2ef} = \sqrt{\frac{1}{T}\int_0^T \Delta u_2^2 dt} = \\ = \sqrt{\frac{1}{T}\int_0^T \left[-N_2 \left\{ \frac{\partial}{\partial t}\left(\int_S \boldsymbol{B}(\boldsymbol{r},t) d\boldsymbol{S} \right) - \frac{\partial}{\partial t}\left(\int_S \boldsymbol{B}^F(\boldsymbol{r},t) d\boldsymbol{S} \right) \right\} \right]^2 dt} = \\ = N_2 \sqrt{\frac{1}{T}\int_0^T \left[\int_S \frac{\partial}{\partial t}\left(\boldsymbol{B}(\boldsymbol{r},t) - \boldsymbol{B}^F(\boldsymbol{r},t) \right) d\boldsymbol{S} \right]^2 dt}\,. \tag{7}$$

For magnetic field solution the simplified 3D model from sensor´s core and primary winding of the coils was created. The task was solved as a magnetostatic problem for chosen value of current in nonlinear environment in the cases when sensor is and is not affected by external force. Analysis of magnetic field was realised using the method of finite elements in COSMOS/EMS program for current density $J = 2,07875844.10^7$ Am^{-2} in wires of primary winding and frequency of current f = 400Hz. Permeability in sensor´s core made from lamellas of ferromagnetic material depends on magnetic inductance B. For the purposes of magnetostatic analysis, magnetization characteristics of material had to be measured. This measurement had been done by Epstein´s device for frequency f = 400 Hz. From the measured and calculated values the graphical functionality B = f (H) magnetization curve for transformator´s metal, from which the lamellas, which create the sensor´s core are made from (Fig. 3) and μ = *f* (B), (Fig. 4).

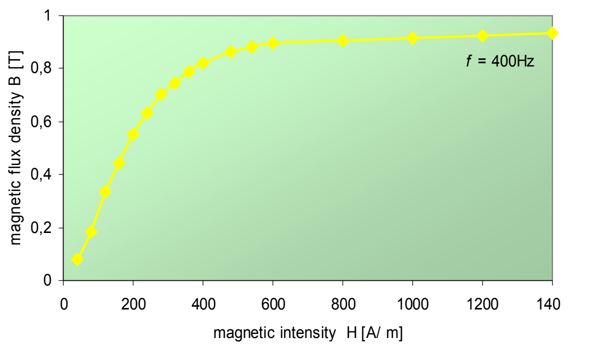

Figure 3 – $B = f(H)$, $f = 400$ Hz

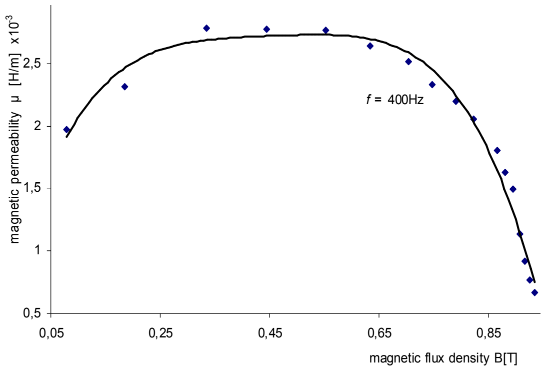

Figure 4 – $\mu = f(B)$, $f = 400$ Hz

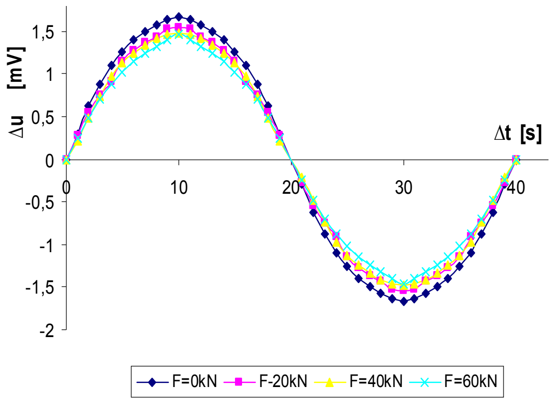

Figure 5 – The dependence $\Delta u = f(\Delta t)$, $f = 400$Hz

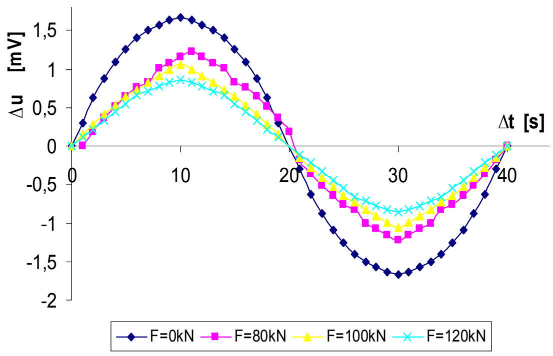

Figure 6 – The dependence $\Delta u = f(\Delta t)$, $f = 400$Hz

MEASUREMENT AND CALCULATION OF THE OUTPUT SIGNAL EMS. For measuring the effective value of output signal the measuring system was designed and created. Its scheme is pictured on Fig. 1. When expressing effective value of sensor´s output power it will be convenient to consider that, that behaviour of sensor´s magnetic induction is harmonic too.

Effective values of output voltage and addition of output voltage, directly proportional to pressure force were calculated using the equations (6) and (7). These values were compared with the measured values. Both of the values are presented in graphical (Fig. 7, Fig. 8) and table (Tab. 1, Tab. 2) form.

Table 1 – Calculated and measured values of output voltage

F [kN]	U_2 [mV] Measured	U_2 [mV] Calculated
0	1620	1609
20	1540	1523
40	1435	1428
60	1304	1324
80	1172	1171
100	1046	1036
120	929	928

Useful signal in %

$$\frac{\Delta U_2}{U_{2n}} = 42{,}7\%$$

Linearity error in %

$0 - 4{,}3$

1,9 Calculation

Table 2 – Calculated and measured values addition of output voltage

F [kN]	ΔU_2 [mV] Measured	ΔU_2 [mV] Calculated
20	80	86
40	185	181
60	316	285
80	448	438
100	574	573
120	691	681

Useful signal in %

$$\frac{\Delta U_2}{U_{2n}} = 42{,}3\%$$

Linearity error in %

$0{,}2 - 4{,}2$

1,9 Measurement

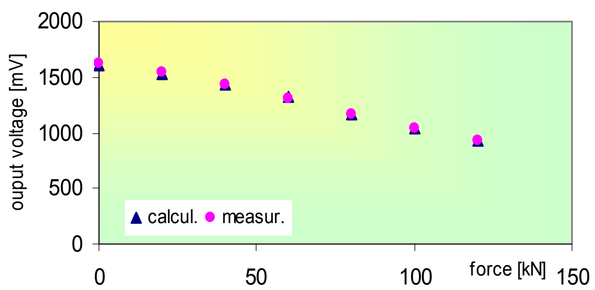

Figure 7 – Calculated and measured values addition of output sensor voltage

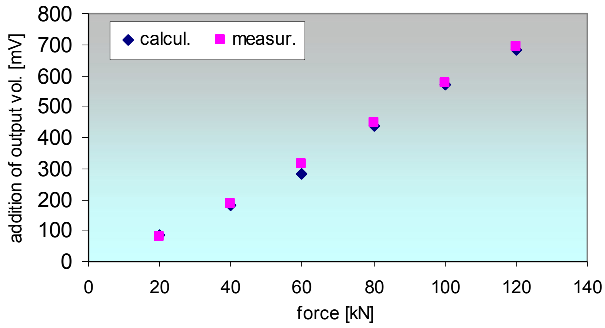

Figure 8 – Calculated and measured values addition of output sensor voltage

CONCLUSION. In the article the relation between input and output EMS pressure force signal was verified. The values of output voltage are dependent on magnetic induction. With the increased pressure force the magnetic induction in sensor´s core decreases, as well as output voltage of the sensor. This was verified with practical measurements. The calculated and measured results comparison shows the differences. The differences are most probably caused by using simplified assumption.

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НЕКОТОРЫЕ МЕТРОЛОГИЧЕСКИЕ ОСОБЕННОСТИ ЭЛАСТОМАГНИТНЫХ ДАТЧИКОВ СИЛЫ НАЖАТИЯ

А. Ходуликова, Д. Ковач
Технический университет Кошице
Парк Коменского, 3, г. Кошице, 04001, Словакия. E-mail: anna.hodulikova@tuke.sk, dobroslav.kovac@tuke.sk

В первой части работы речь идёт о метрологических особенностях эластомагнитных датчиков силы нажатия с нормальным значением 120 кН, которые были спроектированы и изготовлены на кафедре электрической инженерии и электрических измерений FEI TUKE. Эластомагнитные датчики силы нажатия основаны на использовании эффекта Вилари и принадлежат к группе нелинейных систем. Вторая часть работы посвящена проверке входного напряжения эластомагнитных датчиков силы нажатия с целью определения соответствия значений магнитной индукции, полученных путём компьютерной симуляции трёхмерной модели в среде COSMOS/EMS, экспериментальным результатам, полученным путём измерения входного напряжения.

Ключевые слова: электромагнитные датчики, метрологические особенности, симуляция, выходное напряжение.

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